PREDICTION OF PROPELLANT TANK PRESSURIZATION REQUIREMENTS BY DIMENSIONAL ANALYSIS

by J. F. THOMPSON AND M. E. NEIN
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ABSTRACT

A dimensional analysis of a large number of pressurization tests and computer runs is applied to develop an equation that predicts pressurant requirements for cylindrical and spheroidal propellant tanks with an accuracy of 10 per cent. This method is applicable for preliminary design optimization studies of pressurization systems where the time consumed and expensive use of computers is not warranted.

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TECHNICAL MEMORANDUM X-53218

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RESEARCH AND DEVELOPMENT OPERATIONS

PROPULSION AND VEHICLE ENGINEERING LABORATORY

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DEFINITION OF SYMBOLS

Symbol	Definition	
A	Propellant tank wall surface area	Ft^2
A_D	Distributor area	Ft^2
J	Dimensional constant	$lb_f\ Ft/Btu$
M_w	Pressurant molecular weight	$lb_m/lb\ Mol$
T_a	Ambient temperature	$°R$
T_L	Propellant temperature	$°R$
T_m	Ullage mean temperature at cutoff	$°R$
T_o	Pressurant inlet temperature	$°R$
V	Propellant tank volume	Ft^3
V_i	Initial ullage volume	Ft^3
$\dot{V}_L$	Propellant volumetric drain rate	Ft^3/sec
d_w	Wall thickness	Ft
C_p	Pressurant specific heat	$Btu/lb_m\ °R$
C_{pw}	Wall specific heat	$Btu/lb_m\ °R$
g_c	Dimensional constant	$\dfrac{lb_m\ Ft}{lb_f\ sec^2}$
h_a	Ambient heat transfer coefficient	$Btu/sec\ Ft^2\ °R$
k	Pressurant thermal conductivity	$Btu\ Ft/sec\ Ft^2\ °R$
p	Ullage pressure	lb_f/Ft^2
r	Propellant tank characteristic radius (maximum radius for cylindrical tanks)	Ft

DEFINITION OF SYMBOLS (CONCLUDED)

Symbol	Definition	
R	Universal Gas Constant	lb_f Ft/°R lb Mol
α	Gas Compressibility	(-)
μ	Pressurant viscosity, M/L	lb_m/Ft sec
ρ_w	Wall density, M/L^3	lb_m/Ft^3
θ	Time of pressurization	sec

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SUMMARY

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Pressurant gas requirements for launch and space vehicles may be predicted by analytical models of the pressurization process. However, preliminary design studies require a fast and reasonably accurate method of predicting without resorting to computer programs. Therefore, dimensional analysis of a large number of pressurization tests and computer runs was applied to develop an equation that predicts pressurant requirements for cylindrical and spheroidal propellant tanks with an accuracy of ± 10 per cent.

INTRODUCTION

Although the most accurate method of predicting pressurant requirements is with a computer program that has been varified by experiments, it is advantageous to have a fast, reasonably accurate method to determine the total mass of pressurant gas required without resorting to the computer. This type of analysis is necessary in comparison and optimization studies for preliminary design where the number of possibilities to be considered precludes a detailed computer analysis of each case. This report presents a single, general expression for the total required mass of pressurant; the expression was developed by dimensional analysis of the results of about 30 pressurization tests and 120 simulations on an IBM 7094 Computer.

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DIMENSIONAL ANALYSIS OF TEST AND COMPUTER RESULTS

The total mass of pressurant gas required is a function of the ullage mean temperature at cutoff derived with the gas equation of state,

$$W_{Total} = \frac{pV\ M_w}{\alpha\ RT_m} \tag{1}$$

Therefore, the total pressurant mass required may be calculated if the ullage mean temperature at cutoff can be determined. In the most general case, the ullage mean temperature at cutoff will be a function of 12 system design variables, seven physical properties, the mechanical equivalent of heat, and the gravitational constant:

$$T_m = f(J,\ g_c,\ M_w,\ k,\ \mu,\ c_p,\ r,\ T_o,\ T_L,\ \theta_T,\ V,\ A,$$

$$h_a,\ T_a,\ c_{p_w},\ \rho_w,\ d_w,\ p,\ V_i,\ \dot{V}_L,\ A_D) \tag{2}$$

The 19 variables can be expressed in six fundamental dimensions, length (L), mass (M), time (θ), temperature (T), heat (H), and force (F). The two dimensional constants, J and g_c, are included because heat and force can be expressed in terms of the other four dimensions. The dimensions of each variable are given in Table IV.

Since any equation representing physical phenomena must be dimensionally homogeneous, it must be possible to write equation (2) in a nondimensional form. Therefore, using π as a symbol for a dimensionless group, equation (2) may be written as follows:

$$\pi_1 = f(\pi_2,\ \pi_3,\ -----\pi_i\ ) \tag{3}$$

where the group π_1 contains the ullage mean temperature at cutoff.

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According to Buckingham's theorem, the number of dimensionless groups in equation (3) is given by:

$$i = n-m \tag{4}$$

where n = number of variables

m = maximum number of these variables which will not form a dimensionless group

The quantity m is often equal to the number of fundamental dimensions. The total number of variables in equation (2), including J and g_c, is 22, and the number of fundamental dimensions is six. By trial and error, it was determined that the maximum number of variables in this case that will not form a dimensionless group is indeed six, the number of fundamental dimensions. Therefore, according to equation (4) there will be 16 dimensionless groups in equation (3).

Dimensionless Groups

Because the maximum number of variables that will not form a dimensionless group is six, the 16 dimensionless groups may be determined by choosing six variables to be common to all groups and, in turn, adding each of the remaining 16 variables to the first six to form 16 dimensionless groups. Although any six variables could be chosen as the six to be common to all groups, intuition leads to the choice of the two dimensional constants (J and g_c), the pressurant molecular weight (M_w), thermal conductivity (k), and viscosity (μ) and the propellant tank characteristic radius (r). Adding the ullage mean temperature at cutoff (T_m) to the six common variables yields the first group:

$$\pi_1 = J^a \, g_c^b \, M_w^c \, k^d \, \mu^e \, r^f \, T_m^g \tag{5}$$

now, substituting the dimensions:

$$\left[1\right] = \left[\frac{FL}{H}\right]^a \left[\frac{ML}{F\theta^2}\right]^b \left[M\right]^c \left[\frac{H}{L\theta T}\right]^d \left[\frac{M}{L\theta}\right]^e \left[L\right]^f \left[T\right]^g \quad (6)$$

Since the quantity on the left of equation (6) is dimensionless, the exponent of each of the six dimensions on the right must be zero. This condition determines six simultaneous equations,

$$
\begin{aligned}
\left[L\right] \quad & 0 = a + b - d - e + f \\
\left[M\right] \quad & 0 = b + c + e \\
\left[\theta\right] \quad & 0 = -2b - d - e \\
\left[T\right] \quad & 0 = -d + g \\
\left[H\right] \quad & 0 = -a + d \\
\left[F\right] \quad & 0 = a - b
\end{aligned}
\quad (7)
$$

Simultaneous solution of these equations yields the following:

$$a = g \qquad d = g$$

$$b = g \qquad e = -3g$$

$$c = 2g \qquad f = -4g$$

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Because the value of g is arbitrary, it can be taken as unity and yields the following:

$$a = 1 \qquad d = 1$$

$$b = 1 \qquad e = -3$$

$$c = 2 \qquad f = -4$$

Substituting these values into equation (5) yields the first group π_1:

$$\pi_1 = \frac{J \; g_c \; M_w^2 \; k \; T_m}{\mu^3 \; r^4} \tag{8}$$

The second group π_2 is found in the same manner by adding the pressurant specific heat C_p to the six common variables. Each of the remaining variables is added one at a time to the six common variables, and the remaining dimensionless groups are determined in the same manner as the first two. Then,

$$\pi_2 = \frac{C_p \; \mu}{k} \tag{9}$$

$$\pi_3 = \frac{J \; g_c \; M_w^2 \; k \; T_o}{\mu^3 \; r^4} \tag{10}$$

$$\pi_4 = \frac{J \; g_c \; M_w^2 \; k \; T_L}{\mu^3 \; r^4} \tag{11}$$

$$\pi_5 = \frac{\mu \; r \; \theta_T}{M_w} \tag{12}$$

$$\pi_6 = \frac{V}{r^3} \tag{13}$$

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$$\pi_7 = \frac{A}{r^2} \tag{14}$$

$$\pi_8 = \frac{C_{p_W}\,\mu}{k} \tag{15}$$

$$\pi_9 = \frac{\rho_W\,r^3}{M_W} \tag{16}$$

$$\pi_{10} = \frac{d_W}{r} \tag{17}$$

$$\pi_{11} = \frac{V_i}{r^3} \tag{18}$$

$$\pi_{12} = \frac{g_c\,M_W\,P}{\mu^2\,r} \tag{19}$$

$$\pi_{13} = \frac{h_a\,r}{k} \tag{20}$$

$$\pi_{14} = \frac{J\,g_c\,M_W^2\,k\,T_a}{\mu^3\,r^4} \tag{21}$$

$$\pi_{15} = \frac{M_W\,\dot{V}_L}{\mu\,r^4} \tag{22}$$

$$\pi_{16} = \frac{A_D}{r^2} \tag{23}$$

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Now, the groups π_1, π_4, and π_{14} may be divided by π_3 with no loss of generality, because none of the 16 groups are eliminated in the process. Thus π_1, π_4, and π_{14} may be replaced with π_1', π_4', and π_{14}', respectively, where

$$\pi_1' = \frac{\pi_1}{\pi_3} = \frac{T_m}{T_o}$$

$$\pi_4' = \frac{\pi_4}{\pi_3} = \frac{T_L}{T_o}$$

$$\pi_{14}' = \frac{\pi_{14}}{\pi_3} = \frac{T_a}{T_o}$$

In the same manner, the group π_{11} may be replaced with π_{11}', where

$$\pi_{11}' = \pi_{11}\, \pi_{12} = \frac{g_c\, M_w p\, V_i}{\mu^2\, r^4} \tag{24}$$

This change occurs because the initial ullage mean temperature is proportional to the product pV_i.

It is possible to reduce the number of dimensionless groups necessary in this case by realizing that the wall specific heat, density, and thickness can enter the problem only in the combination $C_{pw}\, \rho_w\, d_w$. which is the wall heat capacity per unit area. Therefore, the groups π_8, π_9, and π_{10} may be combined into a single group π_8'.

$$\pi_8' = \pi_8\, \pi_9\, \pi_{10} = \frac{M_w\, k}{\mu\, r^2\, (C_{pw}\rho_w\, d_w)} \tag{25}$$

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Similarly, it is possible to combine π_{15} and π_{16}. Thus,

$$\pi'_{15} = \frac{\pi_{15}}{\pi_{16}} = \frac{M_w \dot{V}_L}{A_D \mu r^2} \qquad (26)$$

Further, the propellant tank volume and wall surface area should enter the problem as the area-to-volume ratio (A/V). Therefore, the group π_6 and π_7 may be combined into a single group π'_6.

$$\pi'_6 = \frac{\pi_7}{\pi_6} = \frac{A r}{V} \qquad (27)$$

But since the approximate area-to-volume ratio is given by

$$\frac{A}{V} \cong \frac{2 \pi r l}{\pi r^2 l} = \frac{2}{r} \qquad (28)$$

the group π'_6 is nearly a constant and may be eliminated.

Finally, since the Prandtl number (π_2) does not vary greatly, this group may also be dropped. Thus, the number of dimensionless groups necessary in equation (3) was reduced by six.

Since the propellant temperature is the lower limit of the ullage mean temperature, it is logical to replace all temperatures with temperature differences above the liquid propellant temperature (T_L).

Equation (3) may now be expressed in terms of the following ten dimensionless groups (the group numbers having been changed to run from one to ten):

$$\pi_1 = \frac{T_m - T_L}{T_o - T_L} \qquad (29)$$

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$$\pi_2 = \frac{J g_c M_w^2 k (T_o - T_L)}{\mu^3 r^4} \qquad (30)$$

$$\pi_3 = \frac{T_o - T_L}{T_L} \qquad (31)$$

$$\pi_4 = \frac{\mu r \theta_T}{M_w} \qquad (32)$$

$$\pi_5 = \frac{M_w k}{\mu r^2 (C_{pw} \rho_w d_w)} \qquad (33)$$

$$\pi_6 = \frac{g_c M_w p V_i}{\mu^2 r^4} \qquad (34)$$

$$\pi_7 = \frac{g_c M_w p}{\mu^2 r} \qquad (35)$$

$$\pi_8 = \frac{h_a r}{k} \qquad (36)$$

$$\pi_9 = \frac{T_a - T_L}{T_o - T_L} \qquad (37)$$

$$\pi_{10} = \frac{M_w \dot{V}_L}{A_D \mu r^2} \qquad (38)$$

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Curve Fit of Dimensionless Equation

These ten dimensionless groups [equations (29) through (38)] can be used to correlate the results of tests and computer runs according to equation (3). In most cases equation (3) would be written in the following form:

$$\pi_1 = \alpha \; \pi_2^{\beta} \; \pi_3^{\gamma} \; \pi_4^{\delta} \; \pi_5^{\epsilon} \; \pi_6^{\xi} \; \pi_7^{\lambda} \; \pi_8^{\tau} \; \pi_9^{\sigma} \; \pi_{10}^{\zeta} \qquad (39)$$

However, in this case it is necessary to satisfy certain boundary conditions that cannot be satisfied by equation (39). The ullage mean temperature at cutoff must remain finite and not equal to zero as the ambient heat transfer approaches zero. This boundary condition cannot be satisfied by equation (39), but it can be satisfied if the functional dependence on π_8 and π_9 is exponential. Also, as the distributor Reynolds number π_{10} approaches zero, the heat transfer in the tank approaches free convection. Therefore, the boundary condition of finite, non-zero mean temperature, when π_{10} is zero is imposed, dictates an exponential functional dependence on π_{10}. Thus, these boundary conditions can be satisfied by writing equation (3) in the form

$$\pi_1 = \alpha_1 \; \pi_2^{\beta} \; \pi_3^{\gamma} \; \pi_4^{\delta} \; \pi_5^{\epsilon} \; \pi_6^{\xi} \; \pi_7^{\lambda} \; \left(e^{\alpha_2' \; \pi_8^{\tau} \; \pi_9} \right) \left(e^{\alpha_3' \; \pi_{10}} \right) \qquad (40)$$

The coefficients and exponents in equation (40) were evaluated by a curve fit to the data from the computer runs and tests. It was found that the data could be correlated by this equation if the coefficients α_1 and α_3, in the exponentials were taken as functions of π_2 and π_3:

$$\alpha_2' = \alpha_2 \; \pi_2^{\omega} \; \pi_3^{\psi} \qquad (41)$$

$$\alpha_3' = \alpha_3 \; \pi_2^{\phi} \qquad (42)$$

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Equation (40) then becomes

$$\pi_1 = \alpha_1 \, \pi_2^{\beta} \, \pi_3^{\gamma} \, \pi_4^{\delta} \, \pi_5^{\epsilon} \, \pi_6^{\xi} \, \pi_7^{\lambda} \left(e^{\alpha_2 \, \pi_2^{\omega} \, \pi_3^{\psi} \, \pi_8^{T} \, \pi_9} \right) \left(e^{\alpha_3 \, \pi_2^{\phi} \, \pi_{10}} \right) \quad (43)$$

where all coefficients and exponents are constants.

It was convenient to divide several groups of equation (43) by powers of ten to obtain numbers more easily handled. Therefore, the final equation used in the curve-fit was

$$\pi_1 = \alpha_1 \left(\frac{\pi_2}{10^{14}} \right)^{\beta} \pi_3^{\gamma} \, \pi_4^{\delta} \, \pi_5^{\epsilon} \left(\frac{\pi_6}{10^{14}} \right)^{\xi} \left(\frac{\pi_7}{10^{14}} \right)^{\lambda} \left[e^{\alpha_2 \left(\frac{\pi_2}{10^{14}} \right)^{\omega} \pi_3^{\psi} \left(\frac{\pi_8}{10^3} \right)^{T} \pi_9} \right]$$

$$\cdot \left[e^{\alpha_3 \left(\frac{\pi_2}{10^{14}} \right)^{\phi} \left(\frac{\pi_{10}}{10^5} \right)} \right] \quad (44)$$

From the curve-fit, the following values were obtained for the coefficients and exponents in equation 44:

$$\alpha_1 = 0.424 \qquad \xi = 0.01416$$

$$\alpha_2 = 0.00210 \qquad \lambda = 0.0620$$

$$\alpha_3 = -0.0292 \qquad \omega = 0.415$$

$$\beta = -0.1322 \qquad \psi = 1.174$$

$$\gamma = -0.1688 \qquad T = 0.765$$

$$\delta = -0.1146 \qquad \phi = 0.1510$$

$$\epsilon = 0.0780$$

Therefore, since $\pi_1 = \dfrac{T_m - T_L}{T_o - T_L}$, equation (44) becomes

$$\frac{T_m - T_L}{T_o - T_L} = 0.424 \left(\frac{\pi_2}{10^{14}}\right)^{-0.1322} \left(\pi_3\right)^{-0.1688} \left(\pi_4\right)^{-0.1146}$$

$$\cdot \left(\pi_5\right)^{0.0780} \left(\frac{\pi_6}{10^{14}}\right)^{0.01416} \left(\frac{\pi_7}{10^{14}}\right)^{0.0620}$$

$$\cdot \exp\left[0.00210 \left(\frac{\pi_2}{10^{14}}\right)^{0.415} \left(\pi_3\right)^{1.174} \left(\frac{\pi_8}{10^3}\right)^{0.765} \left(\pi_9\right)\right]$$

$$\cdot \exp\left[-0.0292 \left(\frac{\pi_2}{10^{14}}\right)^{0.1510} \left(\frac{\pi_{10}}{10^5}\right)\right]$$

This equation is general and is capable of predicting the ullage mean temperature, and thus pressurant mass at cutoff within 10% for cylindrical tanks with rounded bulkheads. FIG 1 shows total pressurant requirements obtained by various investigators for a wide range of tank sizes and system parameters compared with the pressurant weights calculated by equation (44). Excellent agreement is obtained over the entire range of conditions for hydrogen and oxygen pressurization. However, the equation is limited in its application to conditions of constant ullage pressure, pressurant inlet temperature, and ambient heat transfer. The studies indicated that the equation is inaccurate at inlet temperatures less than $100°R$ above the saturation temperature, at ullage pressure below propellant saturation, and for very short expulsion times of less than 50 seconds. The restriction to cylindrical tanks can be removed by proper choice of the characteristic tank radius.

Studies have shown that the characteristic tank radius for oblate spheroids, used in equation (44), should be about two-thirds of the maximum tank radius. This assumption is theoretically justified, because a cylinder having the same volume and surface area as an oblate spheroid has a radius equal to 0.63 times its maximum radius. Further test data and analytical studies are necessary to select the characteristic radius for other geometries.

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Due to the dimensionless nature of equation (44), it is not restricted to any particular propellant, pressurant, or tank size as indicated in FIG 1. Although an uninsulated propellant tank was assumed in the development of this equation, FIG 1 shows good agreement with test results obtained with vacuum jacketed liquid hydrogen tanks.

To simplify the use of equation (44), the pressurant and propellant properties for the case of liquid oxygen pressurized by oxygen and liquid oxygen pressurized by helium were substituted in equation (44), and the following equations were obtained. Since these equations are dimensional, they are applicable only to the case indicated. For liquid oxygen pressurized by oxygen,

$$\frac{T_m - 164}{T_o - 164} = 3.33 \ (T_o - 164)^{-0.297} \ r^{0.1395} \ V_i^{0.01416}$$

$$\cdot \ (C_{p_w} \ \rho_w \ d_w)^{-0.0780} \ p^{0.0762} \ \theta_T^{-0.1146}$$

$$\cdot \ \exp \left[0.001568 \ (T_o - 164)^{-0.304} \ r^{-0.895} \ h_a^{0.765} \ (T_a - 164) \right]$$

$$\cdot \ \exp \left[-120.9 \ (T_o - 164)^{-0.574} \ r^{-2.604} \left(\frac{\dot{V}_L}{A_D} \right) \right] \tag{45}$$

and for liquid oxygen pressurized by helium,

$$\frac{T_m - 164}{T_o - 164} = 3.10 \ (T_o - 164)^{-0.304} \ r^{0.1395} \ V_i^{0.01416}$$

$$\cdot (C_{p_w} \ \rho_w \ d_w)^{-0.078} \ p^{0.0762} \ \theta_T^{-0.1146}$$

$$\cdot \exp \left[0.0000681 \ (T_o - 164)^{-0.1650} \ r^{-0.895} \ h_a^{0.765} (T_a - 164) \right]$$

$$\cdot \exp \left[-5.04 \ (T_o - 164)^{-0.443} \ r^{-2.604} \ \frac{\dot{V}_L}{A_D} \right] \tag{46}$$

The units of all variables in equations (45) and (46) must be those given in the Definition of Symbols. For other combinations of propellant and pressurant, equation (44) must be used. After the ullage mean temperature at cutoff is calculated, and using equation (44), (45),or (46), if applicable, the total mass of required pressurant gas may be calculated from equation (1).

In designing a launch or space vehicle pressurization system, vehicle parameters such as tank volume, engine flowrate, tank material, etc., determined by vehicle mission profile, are fixed input values. However, there are various controllable parameters in a pressurization system that can be used to optimize the system without affecting basic vehicle characteristics. The relative significance of various parameters on pressurant requirements has, therefore, been investigated under another study program. The results of these studies excerpted from reference 1 are presented in FIG 2. From a central origin, representing a reference condition (SATURN V, S-IC Stage) for all parameters, the increase (+Y) and decrease (-Y), of the ullage mean temperature at cutoff is shown as a function of variation of the parameters on the abscissa. The parameters were varied over a range expected for vehicle design. Thus, pressurant inlet temperature can increase or decrease by a factor of 2 from the reference condition, pressure by a factor of 3, tank radius by a factor of 2, expulsion time by a factor 3, etc. It was indicated that the pressurant inlet temperature exerts the greatest influence on the ullage mean temperature. Diminishing return of this effect did not exist within the range of investigation (530°R to 1200°R). The mean temperature increased as the ullage pressure was increased and also as the tank radius was increased. Increasing the tank wall thickness, heat capacity, or density caused a decrease in the mean temperature. The pressurant distributor flow area (A_D) that controls the gas-to-wall forced convection heat transfer coefficient had a significant effect on the mean temperature when A_D was reduced, but no effect at all when flow area was increased. This indicates that the pressurant inlet velocity for the reference systems was chosen at an optimum point. FIG 2 also indicates that helium pressurant must be introduced into a tank at a temperature 1.1 times higher than oxygen pressurant to obtain the same ullage mean temperature.

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CONCLUSIONS

An equation derived by dimensional analysis provides a reasonably accurate method for prediction of pressurant requirements for cylindrical LOX and hydrogen propellant containers. This method is advantageous for preliminary design and optimization studies where the use of large computer programs becomes excessive in cost and time.
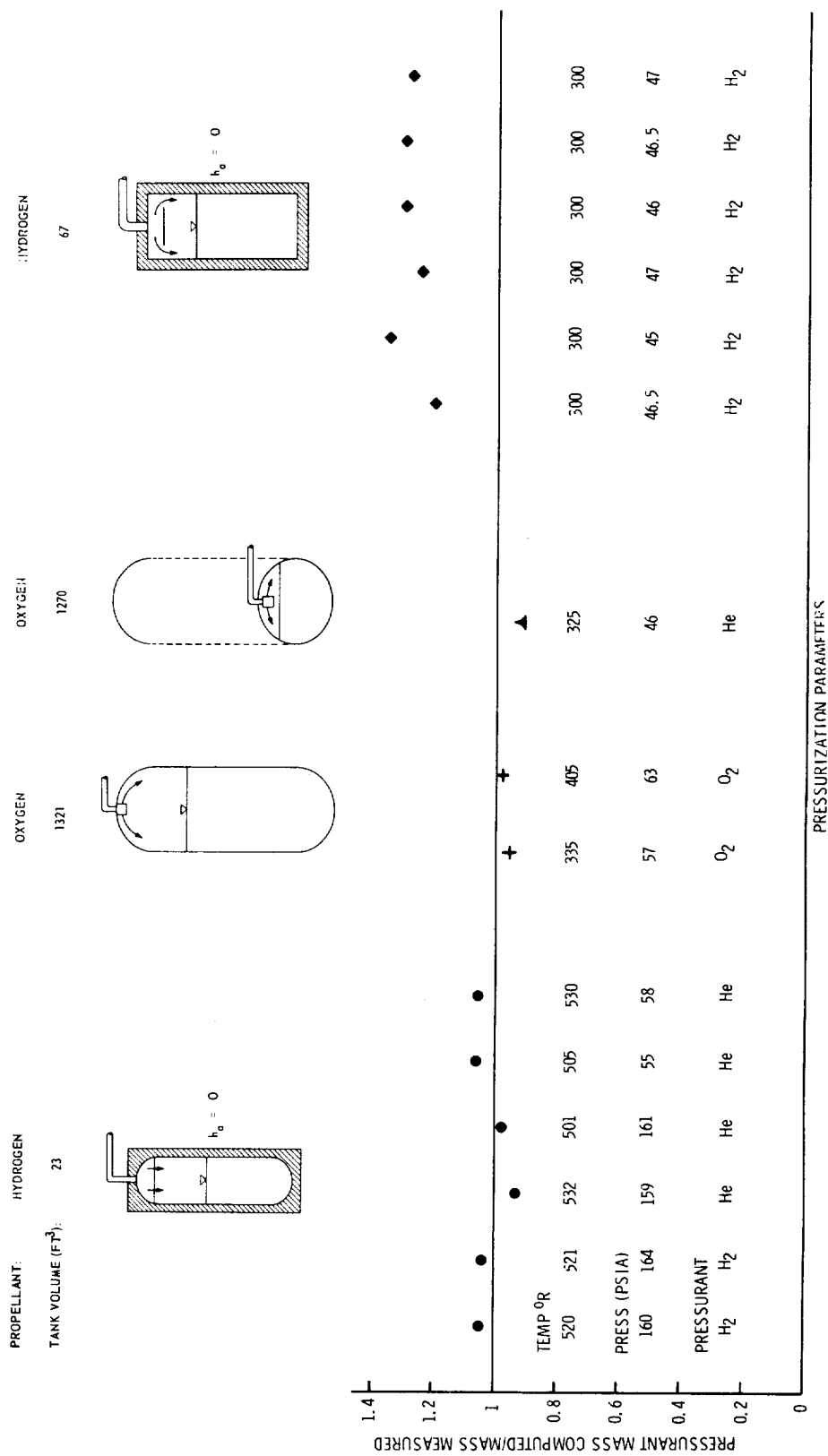
PROPELLANT: HYDROGEN   OXYGEN   OXYGEN   HYDROGEN

TANK VOLUME (FT³): 23   1321   1270   67

PRESSURANT MASS COMPUTED/MASS MEASURED

TEMP °R	520	521	532	501	505	530	335	405	325	500	300	300	300	300	300
PRESS (PSIA)	160	164	159	161	55	58	57	63	46	46.5	45	47	46	46.5	47
PRESSURANT	H₂	H₂	He	He	He	He	O₂	O₂	He	H₂	H₂	H₂	H₂	H₂	H₂

PRESSURIZATION PARAMETERS

FIG 1 COMPARISON OF CALCULATED AND MEASURED PRESSURANT MASS FOR VARIOUS TEST PARAMETERS

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FIG 2 THE EFFECTS OF VARIOUS DESIGN PARAMETERS ON THE MEAN TEMPERATURE AT CUTOFF

17

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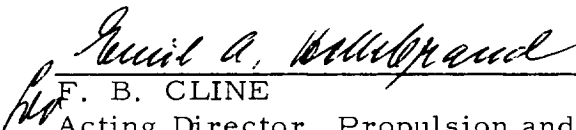This document has also been reviewed and approved for technical accuracy.

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